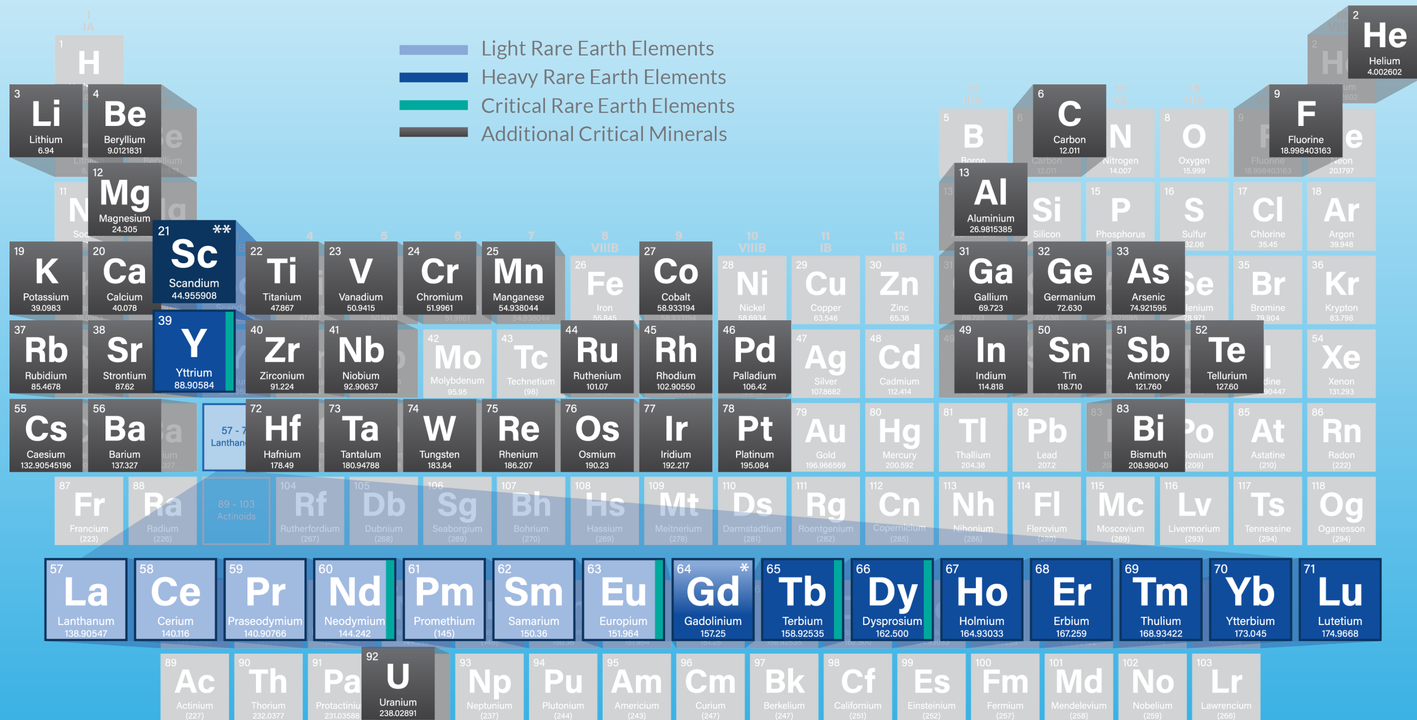
RARE EARTH ELEMENTS AND CRITICAL MINERALS



* Gd: IUPA Light REE; USGS Heavy REE
** Included with rare earth elements

NATIONAL ENERGY TECHNOLOGY LABORATORY

To address the challenge of leading our nation to secure national independence from rare earth element (REE) offshore reliance, DOE performed an initial assessment under its **Feasibility of Recovering Rare Earth Elements** program to assess the potential recovery of REE from coal, coal by-products, and waste materials. This included run-of-mine coal, coal refuse (mineral matter that is removed from coal), clay/sandstone over/under-burden materials, ash (coal combustion residuals), aqueous effluents such as acid mine drainage (AMD), and associated solids and precipitates resulting from AMD treatment. After reporting its findings in the DOE 2015 Report to Congress, the department initiated a multi-year research, development and demonstration (RD&D) effort to demonstrate both the technical and economic feasibility of extracting, separating and recovering REE from these domestic coal-based resource materials. Basic and applied research projects were conducted at national laboratories, small business organizations, and numerous universities. This led (in 2016) to the design, construction, and operation of bench-scale and small pilot-scale facilities, and in 2018 to the production of small quantities (e.g., ~100 gm/day) of 90% (900,000 ppm) high purity, mixed rare earth oxides (MREO) using conventional physical beneficiation and chemical separation processes. Currently, conventional separation process system concepts are being assessed for near-future production of 1–3 tonnes/day of high-purity MREO from coal-based resources in engineering prototype facilities.

RARE EARTH ELEMENTS AND CRITICAL MINERALS

In order to comply with Executive Order 13817 [1], DOE's program expanded its technology development effort in 2019 to include the recovery of critical minerals (CM) from coal-based resources. As a result, DOE's program in 2020, renamed as the **Critical Minerals Sustainability** program, required existing domestic small pilot-scale facilities to co-produce CM in addition to producing REE. In 2021, DOE Fossil Energy Carbon Management's (FECM) program initiated basinal coalition efforts to address the full economic potential value of U.S. natural resources for producing REE, CM, and high-value, nonfuel, carbon-based products, and to holistically assess not only upstream mining of resources and physical separation (e.g., beneficiation), but also midstream processing, separation, recovery and purification of critical and high-value materials, and ultimately onshore downstream manufacturing that incorporates these materials into consumer or national defense products. Additionally, in 2021, efforts were initiated that addressed the development of innovative, cost-reduced processing for the separation of mixed critical minerals into individual or binary, high purity rare earth oxides (REO) and CM, and reduction of these materials to metals for use in alloy production, advanced technology development, and component manufacturing.

[1] Executive Order 13817, A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals, December 20, 2017.

PROGRAM MISSION

The over-arching mission of DOE-NETL's **Critical Minerals Sustainability** program is to rebuild U.S. leadership role in extraction and processing technologies to support an economically, environmentally benign, and geopolitically sustainable U.S. domestic supply chain for production of rare earths and critical minerals for clean energy and national defense.

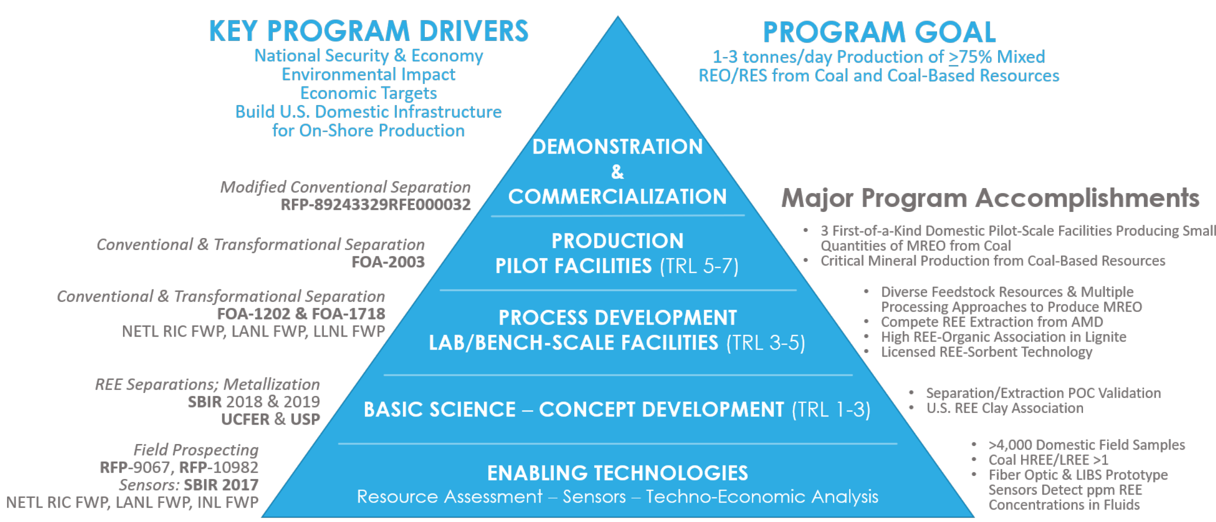
PROGRAM OBJECTIVES AND GOALS

The objectives of this program are to:

- Recover REE and CM from the following sources: domestic coal; coal refuse (mineral matter removed from coal); clay/sandstone over/under-burden materials; ash (coal combustion or gasification residuals); aqueous effluents such as AMD; and associated solids and precipitates resulting from AMD treatment. Additional sources include: legacy coal waste ponds; alternate materials such as produced waters (carbon capture and storage, as well as oil and natural gas produced brines); and associated chemical and industrial waste or waste streams. The intent is to ensure that all REE and CM are recovered in an economically and environmentally benign manner.
- Advance existing conventional processes and develop innovative transformational REE and CM extraction, separation, recovery, and purification processes, as well as processes for reduction to metals.
- Accelerate design, construction, operation and production of REE and CM in domestic engineering-scale prototype separation facilities.

The overall goal of the program is to produce 1-3 tonnes/day of high purity mixed rare earth oxides/salts (MREO/MRES) and CM with production of metals in domestic engineering-scale prototype separation facilities by 2026.

Rare Earth Elements and Critical Minerals Program



For more information, see: netl.doe.gov/coal/rare-earth-elements

PROGRAM PORTFOLIO

As a fully integrated RD&D program, DOE-NETL's efforts uniquely span basic and applied science and technology development (e.g., technology readiness level (TRL) 1-3), through engineering design, construction and operation of bench- and small pilot-scale separation facilities (TRL 3-5), to development of process designs and operation of near-future engineering-scale prototype separation facilities (TRL 7-8).

Technology development in DOE-NETL's federally funded intramural and extramural projects has systematically focused on field prospecting and resource assessment; integration of conventional physical beneficiation and chemical separation or hydrometallurgical processing of feedstock materials to produce high purity coal-based MREO; development of advanced transformational separation processes; techno-economic assessment (TEA) of conventional and transformational separation processes; and optimization and efficiency improvement of conventional separation processes to achieve REE and CM separation process economic viability.

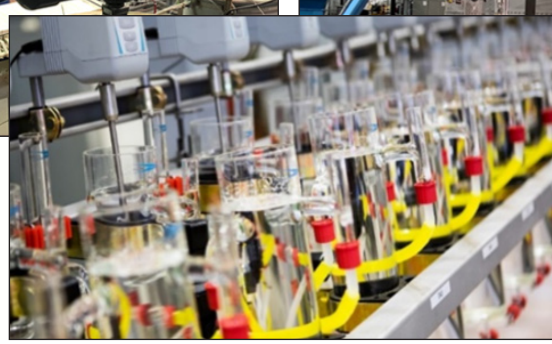
Through DOE-NETL's RD&D program, numerous stakeholder extraction separation and recovery processing approaches have been identified and used to demonstrate the technical feasibility of extracting REE from coal, coal refuse, power generation ash and AMD. To date, these efforts have resulted in the design, construction and operation of three first-of-a-kind, small pilot-scale facilities producing small quantities (e.g., ~100 gm/day) of >98-99% (>980,000-990,000 ppm) high purity MREO from 300 ppm REE-containing coal-based feedstock materials using conventional physical beneficiation and hydrometallurgy (chemical separation), with co-production of CM. Two additional small REE-CM pilot-scale facilities are being readied for operation in 2022.

Small Domestic Pilot-Scale Facilities Producing High Purity MREO and CM (Co, Mn, Ni, Ga, Gd) from Coal-Based Materials

Courtesy of Rick Honacker, University of Kentucky

Roe-Hoan Yoon, Virginia Tech

Courtesy of Prakash Joshi & David Gamliel, PSI



Courtesy of Paul Ziemkiewicz, WVU

In addition, researchers at NETL's Research and Innovation Center (RIC) are championing the development of a novel, data-driven REE and CM resource assessment methodology **– REE-SED Assessment Method –** to predict the occurrence of promising REE and CM bearing deposits associated with coal bearing sedimentary strata, and where possible quantification and prediction of REE and CM resource volumes, and their accessibility and feasibility for recovery of these resources in a sustainable and economical manner. NETL RIC researchers are enhancing their REE embedded critical demand and supply chain database to include CM.

Additionally, researchers at West Virginia University have demonstrated that nearly 100% of the REE in AMD can be recovered, converting small AMD material drying cells (~0.5 acres x ~10-ft deep) into greater than an estimated $250,000 in profitable revenue. Researchers at the University of North Dakota have shown the relative ease of extraction of the primarily contained organically bound REE in lignite using a one-step selective mineral acid leaching process. Researchers at the University of Kentucky in collaboration with researchers at the University of Utah have incorporated *in-situ* sulfuric acid production through microbially-enhanced heap leaching of pyrite in feedstock materials, improving coal refuse processing economics. Using modified lixiviants, researchers at Virginia Tech leveraged simple ion-exchange leaching techniques currently used by industry to extract and concentrate REE from Appalachian coal refuse clay and shale materials.

RARE EARTH ELEMENTS AND CRITICAL MINERALS

In collaboration with Battelle Memorial Institute, Rare Earth Salts (RES) has produced the first individually separated, high purity (>95%) REO from coal-based materials. Researchers at Los Alamos National Laboratory (LANL) have shown the feasibility of transitioning proven actinide separations processing technology to the separation and recovery of REE in the lanthanide series, as well as the development of a portable LIBS-Ramen backpack, similar to the one planned for soil exploration on Mars, for determination of the REE concentration and chemical phase composition in solid coal-based materials.

PROGRAM STRATEGIC PERFORMANCE

This program supports achievement of an important Office of Fossil Energy and Carbon Management strategic objective to recover REE and CM from domestic sources in order to enhance national security and support renewable energy deployment while simultaneously remediating legacy environmental impacts. This will, in turn, help achieve NETL's goal of advancing environmental justice and creating jobs while enabling environmental sustainability for all Americans.

ECONOMIC AND NATIONAL IMPACT

DOE-NETL's rapid and remarkable achievements since 2014 represent the first step towards producing critical materials from coal-based resources and the potential to create and construct onshore supply chain manufacturing facilities that produce consumer, clean energy and national defense products.

Courtesy of
NETL REE-CM Website

Contacts

Mary Anne Alvin
Technology Manager
Rare Earth Elements and Critical Materials
Maryanne.Alvin@netl.doe.gov

John Wimer
Deputy Director
Science & Technology Strategic Plans & Programs
John.Wimer@netl.doe.gov

Grant Bromhal
Acting Director for Minerals Sustainability
Office of Fossil Energy Carbon Management
Grant.Bromhal@netl.doe.gov

Traci Rodosta
HQ Program Manager
Minerals Sustainability
Traci.Rodosta@hq.doe.gov